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A SHAPE ANALYSIS BASED STRATEGY FOR ESTIMATION OF IN VIVO VENTRICULAR WALL ELASTICITY

Jing Xu¹, Marc A. Simon², Timothy C. Wong², and John C. Brigham^{3,1}

¹ Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA, jix57@pitt.edu

² Cardiovascular Institute, School of Medicine, University of Pittsburgh, Pittsburgh, PA 15261, USA, {simonma@upmc.edu, wongtc@upmc.edu}

³ Durham University, School of Engineering and Computing Sciences, Durham DH1 3LE, United Kingdom, john.brigham@durham.ac.uk

SUMMARY

A computational approach is presented and evaluated to estimate the *in vivo* magnitude and spatial distribution of elastic material properties of the heart wall. In particular, this strategy utilizes an optimization-type inverse problem solution procedure with shape analysis based metrics to estimate elastic properties from untagged cardiac images and corresponding hemodynamic measurements. A simulated inverse problem focused on estimating the passive elasticity of the human right and left ventricle wall is examined. The results show that the shape-based approach can accurately estimate the elasticity of the heart wall, although the accuracy and consistency is dependent on the spatial region considered.

Key words: *material characterization, shape analysis, heart wall*

1 INTRODUCTION

There are several cardiovascular diseases that have significant effects on the mechanics of the heart. Pulmonary Hypertension (PH) is one such cardio-pulmonary illness affecting all ages and racial populations that is known to affect the size, shape, and material properties of the heart, particularly the right ventricle [1]. One of the most critical issues in the study and treatment of PH is that there is limited capability to judge both the early stages of this deadly disease, as well as the likelihood of progression to heart failure. Even though a natural and common hypothesis is that the *in vivo* heart mechanics is important to better understanding PH, advances in utilizing this information are relatively limited. One likely significant limiting factor is that while some aspects of the cardiovascular mechanics can be measured and/or estimated well, there is currently not a trusted, clinically applicable method to accurately and consistently estimate the mechanical material properties of the human heart wall *in vivo*. Towards addressing this challenge, an inverse problem solution technique is being developed, and will be presented herein, to estimate the mechanics material properties of the heart wall from clinically attainable cardiac medical images (e.g., CMRI) and measurable hemodynamics. A core component of this approach is the novel use of shape analysis of the imaging data to construct the objective functional for the inverse problem solution procedure.

The primary present objective is to test the potential capability of the inverse problem solution strategy, which is firstly done with simulated inverse problems (i.e., the measurement data is simulated with chosen properties, and then the inverse procedure is applied to see if the chosen properties can be recovered). Although, an important note is that even though the measurement data was simulated for these tests, the simulations were based upon actual human *in vivo* imaging data and corresponding hemodynamic measurements. The following details the data used, and then the simulated inverse problem test procedure. Lastly, preliminary results and discussion are presented.

2 IMAGE DATASET ACQUISITION

Cardiovascular magnetic resonance (CMR) images from a randomly chosen patient who underwent both CMR and right heart catheterization within a 2-day period were utilized in this study. Images were acquired using a 1.5-Tesla Siemens Magnetom Espree (Siemens Medical Solutions, Erlangen, Germany) equipped with a 32-channel cardiac coil. Standard breath-held cine imaging was acquired with steady-state free precession in the short axis orientation spanning the base to apex (6 mm slice thickness, 4 mm skip). Typical imaging parameters included 30 phases per R-R interval, matrix 256 by ~144, flip angle 51 deg, TE 1.11 ms, acceleration factor 3.

3 METHODOLOGY

A bi-ventricle model (i.e., model consisting of just the left and right ventricle) of the diastolic process was created using the finite element method, which was used to both generate the target data and for response estimation during the inverse solution procedure. As the project is motivated by PH, the right ventricle (RV) is the primary concern. Furthermore, typical imaging procedures for PH would focus on the RV, and so the RV would be more accurately captured than the left ventricle (LV). Therefore, the inverse problem target was the RV endocardial surface (i.e., the portion of the heart shape that would be most accurately captured) at end diastole. The inverse problem solution procedure (e.g., [2]) consisted of defining an objective functional that quantifies the difference between the target RV endocardial surface shape and the shape of the RV endocardial surface produced by a finite element analysis with the end diastolic pressure applied to the end systole geometry and an estimate of the unknown material parameters. Then, iterative optimization is applied to estimate the material parameters that minimize the objective functional. A standard interior point gradient-based optimization algorithm was utilized herein. The most critical details of this process are elaborated upon in the following.

3.1 Segmentation and mesh generation

A 3D solid (i.e., volumetric) bi-ventricle geometry at end systole was obtained by manually segmenting the inner and outer surfaces of the RV and LV from each image in MRI stacks, interpolating the slices, and then smoothing the interpolated surfaces using a standard recursive and discrete Gaussian filter within the commercial medical image processing software Simpleware [3] (result shown in Fig. 1). Simpleware was also applied to generate a tetrahedral mesh of the volume suitable for finite element analysis.

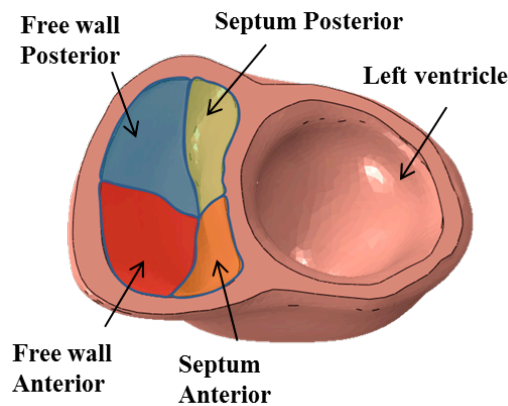


Fig.1 Bi-ventricle volumetric geometry with the material property spatial divisions labeled.

3.2 Constitutive model and boundary conditions

For this preliminary capability study, a simple neo-Hookean constitutive model was adopted. To test the feasibility to estimate heterogeneity, the geometry was divided into 5 regions of different properties (homogeneous within the region though), again primarily focused on the RV, as shown in Fig. 1.

The boundary conditions were defined as follows: the LV endocardial base was constrained in the Z-direction, 10 mm Hg pressure was applied uniformly on the LV inner surface and the RV inner surface was similarly loaded with 5 mm Hg.

3.3. Shape dissimilarity objective functional

Since the expectation is that standard clinical imaging (i.e., without tagging or similar tools available), the comparison of the target RV endocardial surface shape and that estimated by the finite element analysis during optimization is particularly nontrivial. The approach utilized herein is derived from correspondence-based methods for shape analysis. More specifically, the present approach used a variant of harmonic topological mapping [1] to map (i.e., parameterize) both the target and estimated shapes (which are 3D non-overlapping surfaces) to a common domain, a unit sphere. Once mapped, an objective functional can be simply defined in the following form:

$$\|S_{FEM}(\theta, \varphi, \mu) - S_T(\theta, \varphi)\|,$$

where $S_T(\theta, \varphi)$ and $S_{FEM}(\theta, \varphi, \mu)$ are the topologically mapped target and finite element analysis estimated RV endocardial surfaces, θ and φ are the spherical coordinates, and $\|\cdot\|$ is a standard metric norm (L2 used herein) over the sphere domain. μ is the distribution (discrete values herein) of the neo-Hookean shear modulus to be estimated through minimization of the objective functional.

4 RESULTS AND DISCUSSION

Preliminary results of the simulated inverse problem solved with the discussed method with 7 different initial parameter estimates (to start the optimization) are shown in Figs. 2 (value of objective functional at end of optimization) and 3 (error in material parameter estimates at end of optimization). Note that since gradient-based optimization was used, different initial estimates will commonly converge to different final optimized solutions (due to non-convexity).

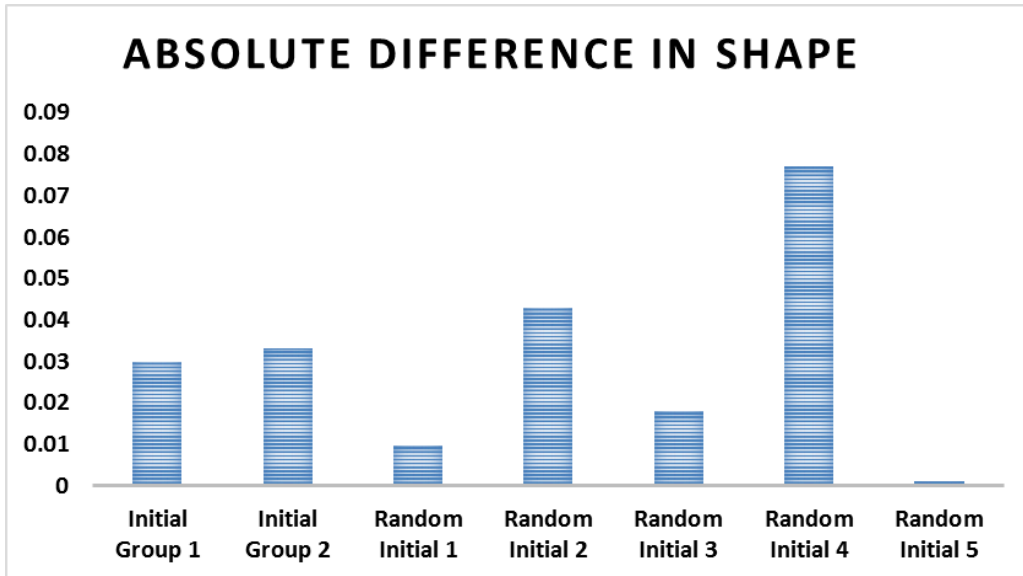


Fig. 2. Absolute difference in shapes between the target and the final estimate from the inverse solution of the 7 trials.

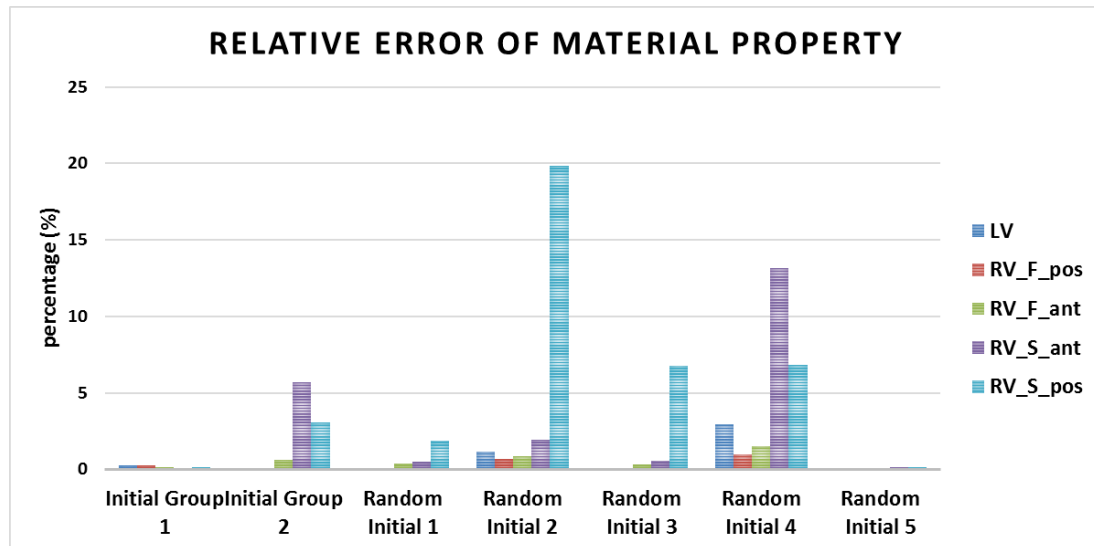


Fig. 3. Relative error between the inverse solution estimate of the 5 material parameters and those used to create the target shape for the 7 trials.

In all cases the optimization procedure was able to reduce the objective functional to a relatively low value, although one case was significantly worse than the rest. Unfortunately, the corresponding material parameter estimates varied more significantly. However, closer examination of the material parameter estimates reveals that in all cases other than the one largest final objective functional value, the estimate of the material properties of the RV free wall were nearly exact. This RV free wall bias is not unsurprising since the inverse problem target was the shape of the RV endocardial surface and the free wall properties contribute to this more so than the septal wall or the LV.

The results indicate that the potential certainly exists to use shape-based objective functionals within an inverse problem scheme to estimate heart wall mechanical material properties. Yet, considerable work still remains to evaluate the proposed approach. In addition to examining more test cases and incorporating more realistic material properties and boundary conditions, several aspects of the solution procedure should be explored further. In particular, examination of alternate shape-based objective functionals is underway, considering alternates such as the Hausdorff distance, and examining their respective effects on accuracy, consistency, and computational efficiency.

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